Copy 2

Proudman Oceanographic Laboratory

Internal Document No. 127

P.O.L.

INTERFACING THE OPERATIONAL STORM SURGE MODEL TO A NEW MESOSCALE ATMOSPHERIC MODEL.

Jane A. Williams and Roger A. Flather

April 2000

National
Environment
Research
Council

PROUDMAN
OCEANOGRAPHIC
LABORATORY

PROUDMAN OCEANOGRAPHIC LABORATORY

Bidston Observatory
Birkenhead, Merseyside, L43 7RA, UK
Tel: 0151 653 8633
Telex: 628591 Ocean B
Fax: 0151 653 6269

Director: Dr. B.S. McCartney

Natural Environment Research Council

Copy 2

POL Internal Document No. 127

Interfacing the Operational Storm Surge Model to a new Mesoscale Atmospheric Model.

By

Jane A. Williams and Roger A. Flather

April 2000

CONTENTS

1. BACKGROUND

Important changes in atmospheric weather prediction models run by the Met. Office have taken place recently, following the installation of the new super-computer (a CRAY T3E) at Bracknell. New models have replaced the "Limited Area Model" (LAM) which previously provided forcing data for all operational surge forecast models. The LAM (resolution ~50km) was superceded by a refined global model (~60km grid) and a new Mesoscale model with resolution ~12km, similar to that of the CS3 surge model. The new Mesoscale model, unlike its predecessor, covers an area large enough to drive the surge models, offering a significant improvement in resolution with potential benefits in surge accuracy.

In order to take advantage of these changes, an investigation to establish how to make best use of the new meteorological forcing data so as to improve surge forecast accuracy was needed. This report describes this study and the results obtained.

2. INTRODUCTION

Since the early 1990s, the storm surge model "CS3" (Continental Shelf model with 3× the resolution of the old "CSX" model; approximately 12km c.f. 36km) has been run operationally at the Met. Office to predict storm surge elevations around the UK. The Storm Tide Forecasting Service (STFS) and Environment Agency use the results for flood forecasting and warning. The necessary met. data to drive the surge model calculations, comprising low-level winds and surface atmospheric pressure fields at hourly intervals, were taken from assimilation and forecast runs of the Met. Office's Limited Area atmospheric Model (LAM), which had resolution of approximately 50km. Figure 1 shows the CS3 model with grid points of LAM. An overview of the operational surge model and its running schedule is given in Flather et al. (1991). Originally, the system ran on a CRAY C90 vector processing supercomputer at Bracknell. A CRAY T3E "massively parallel" machine replaced this and in 1997 the system was updated to run efficiently on multiple T3E processors (Smith, 1997).

The increased power and capacity of the new computer systems the Met. Office allowed the introduction of new improved atmospheric models. Until late 1997, three atmospheric models were in operational use: a global model of resolution ~90km; the limited area model LAM (~50km resolution); and a Mesoscale model (MES) (~18km resolution). These three models have been replaced by two new models; a high-resolution global model of ~60km resolution and a Mesoscale model with resolution ~12km. During the transition period from late 1997, outputs from the new global model were processed by the Met. Office to give fields identical in format and structure to those produced directly by LAM. These LAM "look-alike" (LAMLA) data sets were used to force surge models after LAM was withdrawn in April 1998.

The domain of the new Mesoscale (MES) atmospheric model covers the whole NW European continental shelf including the CS3 region. The MES model is based on a rotated latitude/longitude grid with pole at 37.5°N and 177.5°E. It has 182 rows and

146 columns and resolution of 0.11° (which approximates to 12km). Figure 2 shows the MES grid points superimposed on the CS3 surge model. The high-resolution mesoscale fields could therefore be used to drive CS3 and other surge models. This should improve the accuracy of surge forecasts. For example, the development of small-scale meteorological features such as fronts and secondary depressions should be resolved and predicted more accurately on the 12km MES grid than is possible on the 50km LAM grid. Important cases when the failure of atmospheric models to correctly predict such situations led to poor surge forecasts and failures in flood warnings have been described by Proctor and Flather (1989) and Flather and Smith (1993). In addition, the 12km MES grid will represent land topography and importantly distinguish between "land" and "sea" much more accurately than could LAM. Since the surface roughness, stress and wind speeds differ significantly between land and sea, more accurate and detailed wind forcing in coastal areas should also result.

A further aspect of the LAM forcing for the surge models introduces further uncertainty in forecasts. This is the use of “low-level” winds. These are winds from the lowest level represented in the atmospheric model, $\sigma = 0.997$, where σ is the vertical co-ordinate used in the model. The corresponding height above the surface is that at which the atmospheric pressure is 0.997 × the sea-surface atmospheric pressure (p_a). This is nominally about 25m above the surface but the height depends on p_a and conditions (e.g. temperature and density of air) in the atmospheric boundary layer. Since the wind speed varies with height these factors modify surface stress estimates, with uncertain effects on surge predictions. These considerations led to the provision for the first time of winds at the standard height of 10m above the surface for use in forcing operational surge (and wave) models, providing a consistent basis for estimating surface stress in the future.

The above changes imply systematic differences between LAM and MES forcing of surge models which needed to be investigated, understood and accounted for in the new surge forcing scheme. To this end, it was hoped that a preliminary study could be carried out to identify problems and establish an initial interface between MES and CS3 before the start of the 1998-99 surge season. A more complete investigation would then follow using larger data sets, generated as the new models ran, to optimise the surface forcing and produce an improved scheme. This required that a few months of MES wind and pressure data were archived at Bracknell including a representative sample of storm events for study. Unfortunately, the introduction of the Mesoscale model and setting up of the data archives by the Met. Office were delayed so the initial interface had to be set up with test data and subsequent optimisation was less complete than hoped.

The report is organised as follows. Section 3 describes the derivation of meteorological forcing used for LAM data and the setting-up of testing of the initial interface for MES forcing. Section 4 contains a description of the new interface based on the Charnock (1955) formulation. Test runs and results are described in Section 5 and a summary is given in Section 6.

3. METEOROLOGICAL FORCING FOR LAM AND AN INITIAL SCHEME FOR MES

The storm surge models compute numerical solutions of the basic depth averaged equations, which can be written in vector form as

$$\frac{\partial \zeta}{\partial t} + \nabla . (D\boldsymbol{q}) = 0 \qquad [1]$$

$$\frac{\partial \boldsymbol{q}}{\partial t} + \boldsymbol{q}.\nabla \boldsymbol{q} - f\,\boldsymbol{k} \times \boldsymbol{q} = -g\nabla(\zeta - \bar{\zeta}) - \frac{1}{\rho}\nabla p_a + \frac{1}{\rho D}(\tau_s - \tau_b) + A\nabla^2 \boldsymbol{q} \qquad [2]$$

where: t is time; ζ the sea surface elevation; $\bar{\zeta}$ the equilibrium tide; $\boldsymbol{q}$ the depth-mean current; τ_s the wind stress on the sea surface; τ_b the bottom stress; p_a atmospheric pressure on the sea surface; D the total water depth ($D = h + \zeta$, where h is the undisturbed depth); ρ the density of sea water, assumed uniform; g the acceleration due to gravity; f the Coriolis parameter ($= 2\omega \sin\varphi$, where ω is the angular speed of rotation of the Earth and φ is the latitude); $\boldsymbol{k}$ a unit vector in the vertical; and A the coefficient of horizontal diffusion. Eqn [1] is the continuity equation expressing conservation of volume. Eqn [2] equates the accelerations (left hand side) to the force per unit mass (right hand side). The forcing terms in Eqn [2] which give rise to storm surges are those representing wind stress and the horizontal gradient of surface atmospheric pressure.

Wind stress in the surge model is calculated from the mean wind vector using a quadratic stress law

$$\tau_s = C_d\, \rho_a \boldsymbol{W} |\boldsymbol{W}|, \qquad [3]$$

where τ_s is the surface stress; ρ_a the density of air; C_d the drag coefficient; and for LAM forcing $\boldsymbol{W}$ is the wind vector at $\sigma = 0.997$ (level 1 in the LAM model). The drag coefficient is that derived from observations by Smith and Banke (1975),

$$C_d \times 10^3 = 0.63 + 0.066|\boldsymbol{W}|. \qquad [4]$$

The surface pressure gradient term, ∇p_a, is computed using finite differences from surface pressures interpolated from the atmospheric model grid to surge model elevation grid points.

An initial interface, creating the mechanism to interpolate parameters between the MES atmospheric model and CS3 and using the above formulation was set up and tested for running on the CRAY T3E at the Met. Office and on workstations at POL. Runs were carried out from POL on the T3E, twice each day from early-November 1998. Evaluation of results by POL and STFS was disappointing, with surges substantially under-predicted. Further investigation in December 1998 revealed that MES model wind levels were different from LAM levels: LAM level 1 was at $\sigma =$

0.997012 (about 25m above the surface), whereas MES level 1 was at $\sigma = 0.998812$ which corresponds to about 10m.

Wind speed increases approximately logarithmically with height z above the surface,

$$W(z) = (U_* / \kappa) \ln(z / z_0), \qquad [5]$$

where z_0 is the aerodynamic roughness length, U_* is the friction velocity (defined by $U_*^2 = \tau_s / \rho_a$), and κ is von Karman's constant. With suitable assumptions about z_0, a fair approximation is $W(25\text{m})/W(10\text{m}) \approx 1.1$. Since the stress varies as wind speed squared, this suggests that wind stresses derived from MES level 1 winds using [3] and [4] would be about 20% less than equivalents computed from LAM level 1 winds. This explained the general underprediction and an adjustment in which MES level 1 winds were simply increased by the factor 1.1 was introduced. The test runs at Bracknell carried out by POL continued.

Met. Office began routine "pre-operational" tests of this system with four CS3 runs (forecasts starting at 0000Z, 0600Z, 1200Z and 1800Z) per day during January 1999. Evaluation during the trial suggested results were much better than with the standard formulation but still not providing acceptable accuracy. The reasons were not clear. Met. Office continued development of the MES model during this period and several changes were introduced to improve its performance.

4. REVISED SURFACE STRESS FORMULATION

Following discussion with Met. Office staff and further consideration of alternative stress formulations taking into account a number of additional factors, it was decided in future to use 10m atmospheric model winds to force the surge model, and for the present to use the Charnock (1955) formulation. This would

- avoid ambiguities associated with the definition of 'level 1' winds in future atmospheric models, providing a consistent and standard approach, and
- allow a treatment of stress at the sea surface consistent with the atmospheric boundary layer formulation in the MES model which also uses the Charnock surface stress formulation.

From dimensional analysis, Charnock (1955) obtained

$$gz_0 / U_*^2 = \beta, \qquad [6]$$

where β is the Charnock "constant". So, the roughness length, associated with the surface wave field, increases linearly with surface wind stress. From the logarithmic variation of wind speed with height z above the surface, [5], it follows that the drag coefficient C_Z for wind at height z above the sea surface is

$$C_z = [(1/\kappa)\ln\{gz/(\beta C_z W^2(z))\}]^{-2}. \qquad [7]$$

The Charnock drag coefficient for 10m winds is obtained by setting $z = 10$ in [7]. A simple iterative method can be used to calculate the drag coefficient C_Z for a given wind speed W_Z at height z.

The above formulation contains one adjustable parameter β, the Charnock "constant". Estimates of β range from 0.012 to 0.035. The Met. Office MES model uses $\beta = 0.012$. This value is close to that given by Smith (1988) who found that a value of $\beta = 0.011$ gave a good fit to observations at non-coastal locations. In surge model studies, various values for the Charnock parameter have been used. For example, Mastenbroek et al. (1993), in a model investigation of the influence of wind waves on storm surges, found that $\beta = 0.032$ gave the best results, similar to those from a more complex wave-dependent formulation. With the Smith and Banke drag coefficient [4] and quadratic surface stress [3] with 10m winds, surges were under-predicted by 20%.

In a preliminary study using equations [3] – [7], an appropriate relationship between winds at 10m and at $\sigma = 0.997$, alternative assumptions and values of β were tested by comparing surface stress estimates over a full range of wind speeds. $\beta = 0.012$ was found to underestimate stresses substantially as compared with those derived from the standard LAM formulation. $\beta = 0.032$ overestimated by a smaller margin. After some experimentation, $\beta = 0.0275$ in the Charnock equation with 10m winds was found to give the closest agreement with values of wind stress derived using Smith and Banke and LAM ($\sigma = 0.997$) winds. Figure 3 shows the close agreement between surface stress variations with wind speed using each of these formulations.

As a final check, the Charnock scheme was implemented in the surge model and tested by running the model with a range of values of β. These tests are described in the next section.

5. TEST RUNS AND RESULTS

Work on completing and testing the surge model interface to MES 10m winds could not start until the Met. Office began routine archival of the necessary data sets and data for a suitably long period were accumulated. It was hoped that a Mesoscale data archive including 10m winds would be set up and operational from the start of the 1998/1999 surge season (September 1998). However, due to various problems, data were not consistently and reliably archived until late January 1999. After a month's archive had accumulated the MES wind (10m and level 1) and pressure data covering February 1999 were transferred to POL. These first sets of MES data were received at POL during May 1999. February 1999 was a moderately stormy month with two significant surge events occurring on the East coast. The first produced a surge of approximately 1.5m at Lowestoft on 5th and the second slightly smaller event occurred on 17th. However there were no significant events on other coasts. Test runs were carried out on workstations at POL with the aim of establishing a scheme that would provide results of acceptable accuracy.

Five runs were carried out using various combinations of wind forcing and surface stress formulations as discussed above. Table 1 shows a summary of the runs:

Run ID	Met. data	Wind level	Surface stress	Scaling factor
L1	LAMLA	1	Smith & Banke	1
M1	MES	1	Smith & Banke	1.1
M101	MES	10m	Smith & Banke	1
M111	MES	10m	Charnock ($\beta = 0.032$)	1
M112	MES	10m	Charnock ($\beta = 0.0275$)	1

Table 1. Summary of runs carried out.

Run L1 had been done using previously archived LAM "look-alike" met forcing data so surge model fields for 1st February were available to permit a warm-start. After a five-day spin-up period, the model was run for a February 1999 for tide only. The tide + surge runs with mesoscale forcing data were then run from a "tepid start" condition using data from the tide run as initial conditions. Run M1 involved applying a scaling factor to the winds to account for the difference in height of σ level 1 between LAM and MES. Runs M101, M111 and M112 used the mesoscale winds that were defined at 10m. Run M101 used the standard Smith & Banke formulation for surface stress. Run M111 applied the Charnock formulation with the parameter $\beta = 0.032$ as used in studies by Mastenbroek et al. (1993). Run M112 used a value $\beta = 0.0275$, chosen to provide a "best" approximation to the stresses based on LAM winds and the Smith and Banke formulation.

Observed surge residuals were obtained from the National Tide Gauge Network for February 1999 and used as a basis for evaluating the performance of each of the five runs. Standard statistics similar to those used by POL in routine monitoring of operational surge forecasts were applied to hourly time-series. Since no significant surge activity occurred during this period on the West or South coasts, only East coast ports were considered in the statistical analysis. The results are listed for East coast ports in Table 2. Plots of time series of surge elevations from observations and the model runs are shown in Figure 4 for selected East coast ports.

Differences in the statistics are rather subtle, making it difficult to draw clear conclusions on the basis of this rather short period for comparison. Overall, the largest RMS and 'minimum' errors are from run M101, reflecting an under-prediction of surges using 10m winds with the Smith and Banke drag coefficient. RMS errors from the best MES forced solutions (M1, M111 and M112) are similar in magnitude to those from the standard LAM results (L1), though the MES errors seem slightly worse in the NW and better in the SE than those from LAM. MES level 1 winds adjusted to ~25m and used with Smith and Banke (run M1) give surges which are almost identical to those obtained from 10m winds using Charnock and $\beta = 0.0275$ (run M112), as might be expected from Figure 3.

The time-series plots, Figure 4, confirm the general under-prediction of surges from run M101 (red lines). Of the other results, the surge peak on 4th February tends to be over-predicted, and the second on 5th February under-predicted. The MES forced surges are all very similar in shape, but scale up or down according to the drag coefficient applied. The LAM forced solution has a slightly different basic shape, apparent only from close examination of the plots (e.g. at Sheerness on 7th February where lines cross after the surge minimum) but confirming real differences in the meteorological fields from the two atmospheric models. Time series for Aberdeen show an offset between the model and observed surges which is due to seasonal effects.

Although the data sets are limited, results show that surges computed using the combination of MES winds defined at 10m in conjunction with the Charnock parameterisation of surface stress and $\beta = 0.0275$ are very close to those produced in the existing system.

6. CONCLUSIONS

An interface to enable the operational storm surge model to be run with forcing data from the new Mesoscale atmospheric model has successfully been set up and tested. This involved firstly setting up procedures to interpolate from the atmospheric model to the surge model grid and secondly an investigation to select the most appropriate surface stress formulation and wind forcing combination.

In order to avoid the need to revise the interface should the computational levels in the boundary layer of the atmospheric model change in the future, it was decided to standardise on the use 10m model winds to force surge models from now on.

Unfortunately problems in setting up the necessary archive procedures at Bracknell, delayed the start of reliable 10m wind archives and, as a result test runs were limited to one month – February 1999. From these limited tests, the best option to maintain the present standard of surge forecast accuracy was to use the Charnock surface stress formulation with an appropriate β parameter ($\beta = 0.0275$). This combination gave surge residuals of comparable accuracy to using LAM with Smith & Banke surface stress.

A much more extensive investigation is clearly desirable, but was not possible due to the lack of archived data and the time constraints imposed by the Met Office year-2000 "freeze". A target date of 14 July 1999 for the switch to MES forcing for the operational system was, therefore, agreed and implemented at the Met. Office.

Careful monitoring during the 1999/2000 season has been carried out both by POL and STFS. After initially rather disappointing results due to poor performance of the MES model, accuracy has now improved and is acceptable to STFS. Clearly a more comprehensive investigation using longer sets of archived Mesoscale model fields would allow the stress formulation to be tuned for best results under a wider variety of meteorological conditions and for the South and West coasts. The procedures established here for driving surge models with data from the Mesoscale model and the archive of MES wind and pressure fields accumulating at Bracknell, makes such future studies possible.

ACKNOWLEDGEMENTS

The authors would like to thank staff at the Met. Office, in particular Wendy Hardy, for providing useful information to help set up and test the surge model interface to the Mesoscale model, and Mike Bush for information on the boundary layer formulation in the Mesoscale model.

This work was funded by MAFF under contract no FD1201.

REFERENCES

CHARNOCK, H. 1955. Wind Stress on a Water Surface. *Quarterly Journal of the Royal Meteorological Society*, **81**, 639-640.

FLATHER, R.A., PROCTOR, R. and WOLF, J. 1991. Oceanographic Forecast Models. pp. 15-30 in, *Computer Modelling in the Environmental Sciences*, (ed. D.G. Farmer and M.J. Ryecroft). Oxford: Clarendon Press. 379pp.

FLATHER, R.A. and SMITH, J.A. 1993. Recent progress with storm surge models - results for January and February 1993. pp.6.2.1-6.2.16 in, *Proceedings of the MAFF Conference of River and Coastal Engineers*, 5-7 July 1993, University of Loughborough.

MASTENBROEK, C., BURGERS, G. and JANSSEN, P.A.E.M. 1993. The Dynamic Coupling of a Wave Model and a Storm Surge Model through the Atmospheric Boundary Layer. *Journal of Physical Oceanography*, **23**, 1856-1866.

PROCTOR, R. and FLATHER, R.A. 1989. Storm surge prediction in the Bristol Channel - the floods of 13 December 1981. *Continental Shelf Research*, **9**, 889-918.

SMITH, J.A. 1997. The migration of the operational storm surge model from the CRAY C90 to the CRAY T3E. (Report to MAFF.) POL Internal Document No. 120. 11pp. + Figs. & Tables.

SMITH, S.D. and BANKE, E. 1975. Variation of the Sea Surface Drag Coefficient with Wind Speed. Quarterly Journal of the Royal Meteorological Society, **101**, 665-673.

SMITH, S.D. 1988. Coefficients for Sea Surface Wind Stress, Heat Flux, and Wind Profiles as a Function of Wind Speed and Temperature. Journal of Geophysical Research, **93**, 15467-15472.

Run L1	Sample	RMS Error	Mean	SD	Max Error	Min Error
Stornoway	398	0.20	0.19	0.07	0.36	-0.11
Wick	672	0.19	0.17	0.07	0.35	-0.12
Aberdeen	672	0.15	0.13	0.06	0.34	-0.19
North Shields	672	0.10	0.06	0.07	0.30	-0.34
Whitby	672	0.09	0	0.09	0.24	-0.36
Immingham	672	0.13	0.03	0.13	0.54	-0.46
Cromer	672	0.13	-0.05	0.11	0.23	-0.66
Lowestoft	672	0.14	-0.04	0.14	0.26	-0.76
Felixstowe	672	0.11	0.01	0.11	0.36	-0.63
Sheerness	672	0.13	-0.02	0.13	0.48	-0.57
Run M1						
Stornoway	398	0.22	0.21	0.07	0.42	-0.16
Wick	672	0.21	0.20	0.07	0.37	-0.08
Aberdeen	672	0.16	0.14	0.06	0.33	-0.11
North Shields	672	0.10	0.07	0.07	0.32	-0.18
Whitby	672	0.08	0	0.08	0.24	-0.32
Immingham	672	0.14	0.03	0.14	0.51	-0.51
Cromer	672	0.11	-0.05	0.10	0.23	-0.52
Lowestoft	672	0.14	-0.04	0.14	0.32	-0.73
Felixstowe	672	0.10	0.01	0.10	0.3	-0.58
Sheerness	672	0.12	-0.04	0.11	0.41	-0.64
Run M101						
Stornoway	398	0.21	0.20	0.08	0.41	-0.16
Wick	672	0.20	0.18	0.07	0.38	-0.10
Aberdeen	672	0.14	0.12	0.07	0.32	-0.22
North Shields	672	0.10	0.04	0.09	0.30	-0.37
Whitby	672	0.11	-0.03	0.10	0.24	-0.54
Immingham	672	0.14	0	0.14	0.43	-0.58
Cromer	672	0.17	-0.10	0.13	0.21	-0.70
Lowestoft	672	0.18	-0.09	0.15	0.24	-0.96
Felixstowe	672	0.13	-0.03	0.12	0.24	-0.76
Sheerness	672	0.16	-0.09	0.13	0.38	-0.80
Run M111						
Stornoway	398	0.23	0.21	0.07	0.42	-0.16
Wick	672	0.22	0.21	0.06	0.37	-0.07
Aberdeen	672	0.16	0.15	0.06	0.34	-0.10
North Shields	672	0.11	0.08	0.07	0.32	-0.17
Whitby	672	0.08	0.01	0.08	0.24	-0.31
Immingham	672	0.14	0.04	0.14	0.53	-0.53
Cromer	672	0.11	-0.04	0.10	0.23	-0.49
Lowestoft	672	0.14	-0.03	0.14	0.37	-0.69
Felixstowe	672	0.10	0.02	0.09	0.32	-0.55
Sheerness	672	0.12	-0.04	0.12	0.46	-0.62
Run M112						
Stornoway	398	0.22	0.21	0.07	0.41	-0.16
Wick	672	0.21	0.20	0.07	0.37	-0.07
Aberdeen	672	0.16	0.14	0.06	0.33	-0.12
North Shields	672	0.10	0.07	0.07	0.32	-0.20
Whitby	672	0.08	0	0.08	0.24	-0.34
Immingham	672	0.14	0.03	0.14	0.52	-0.54
Cromer	672	0.11	-0.05	0.10	0.23	-0.52
Lowestoft	672	0.14	-0.03	0.14	0.33	-0.73
Felixstowe	672	0.10	0.01	0.10	0.30	-0.58
Sheerness	672	0.12	-0.04	0.11	0.40	-0.65

Table 2. Statistics for east coast locations – February 1999.

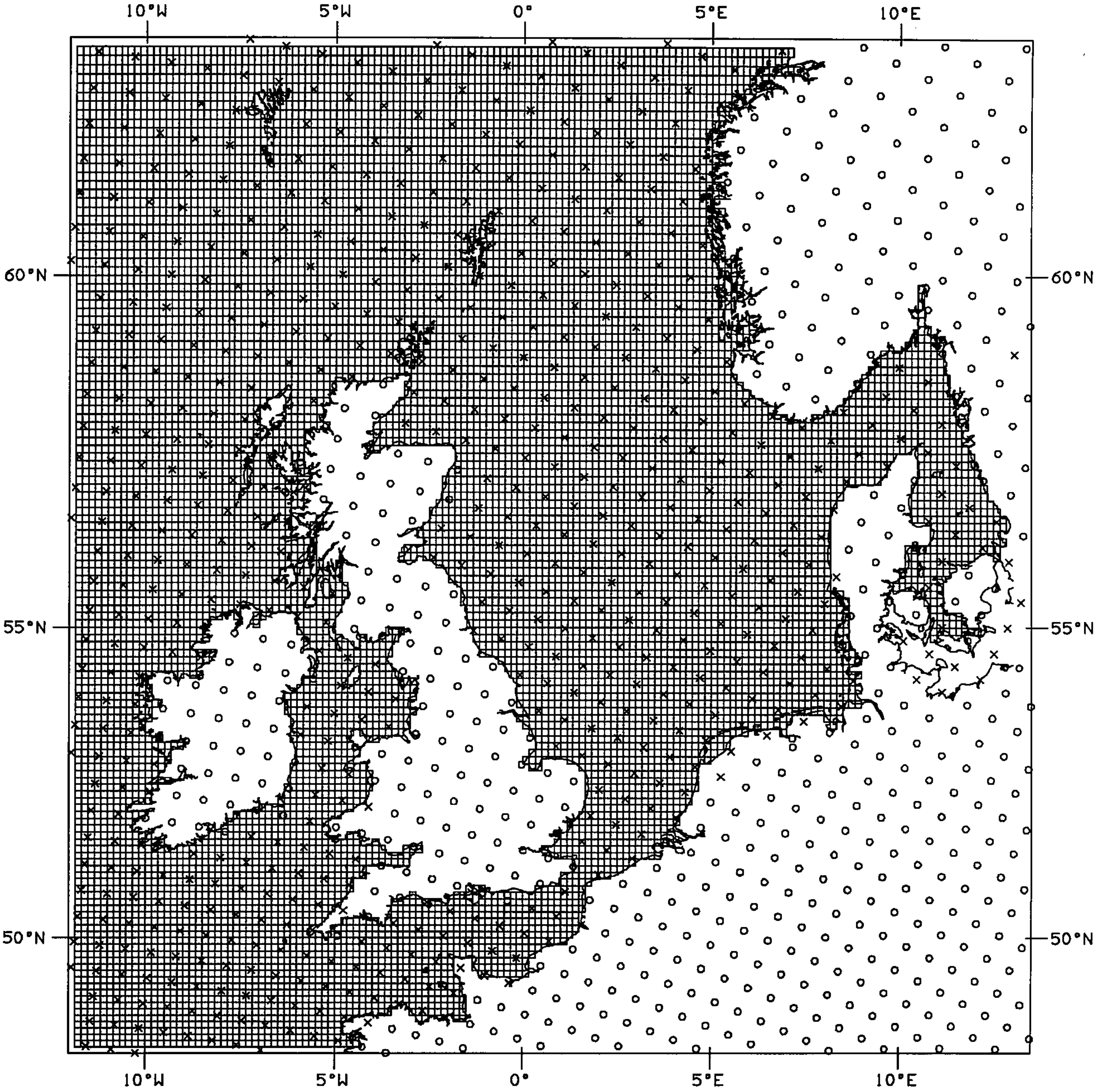

Figure 1. CS3 model grid with LAM atmospheric model points.

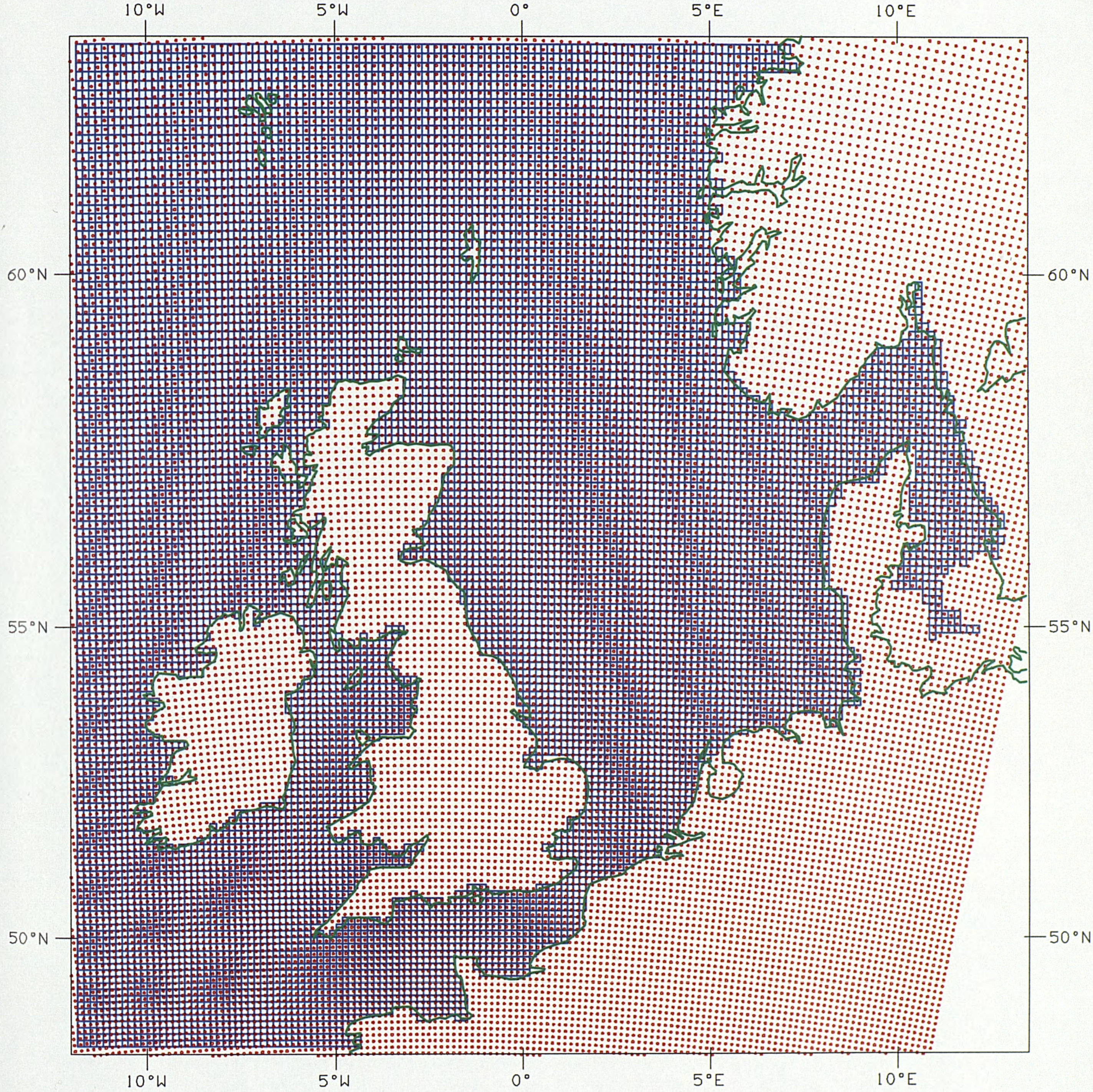

Figure 2. CS3 model grid with mesoscale atmospheric model points

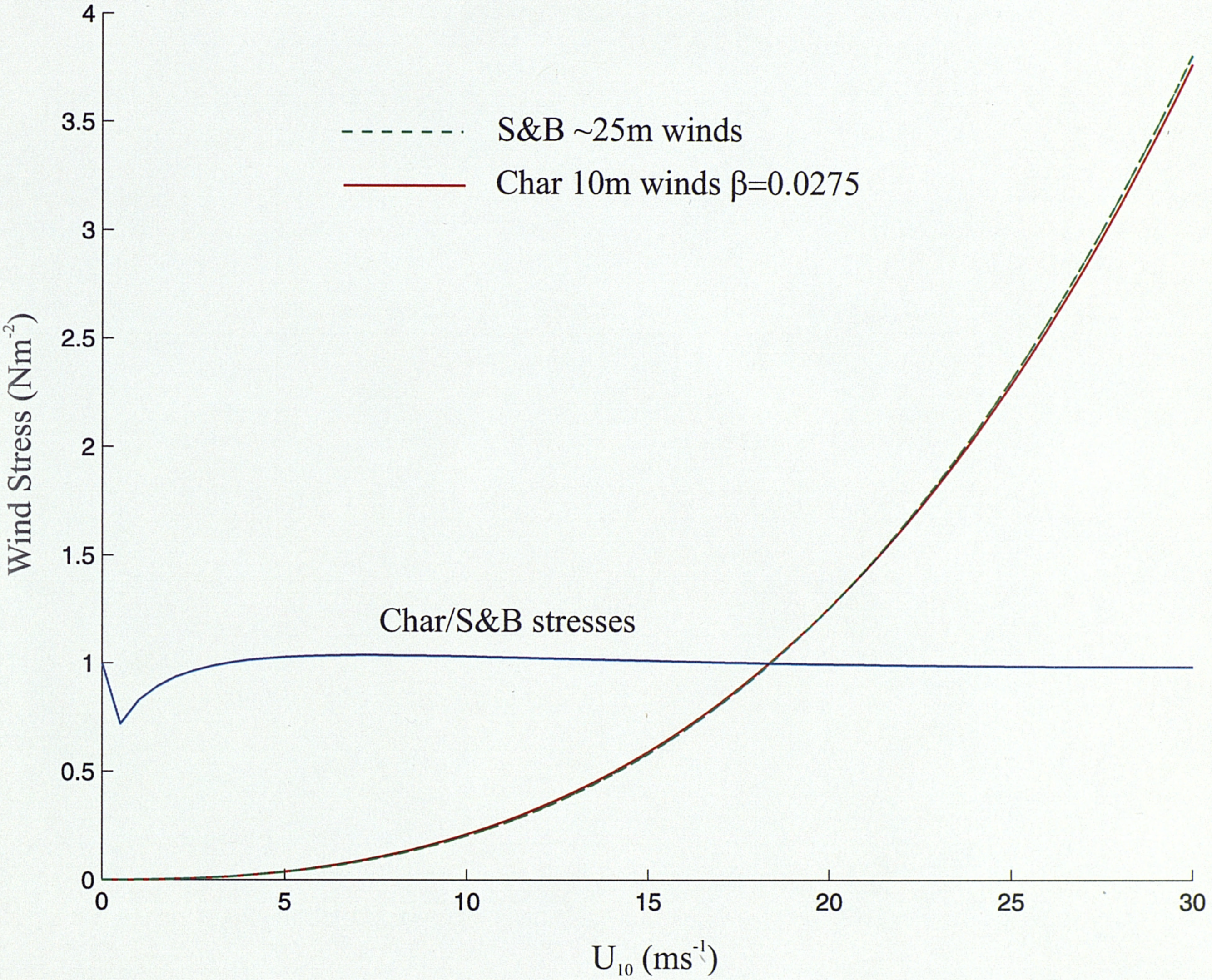

Figure 3. Variation of surface stress with wind speed. Comparison of estimates using LAM with the Smith & Banke drag coefficient and MES 10m winds with Charnock. The ratio (blue line) is very close to 1.

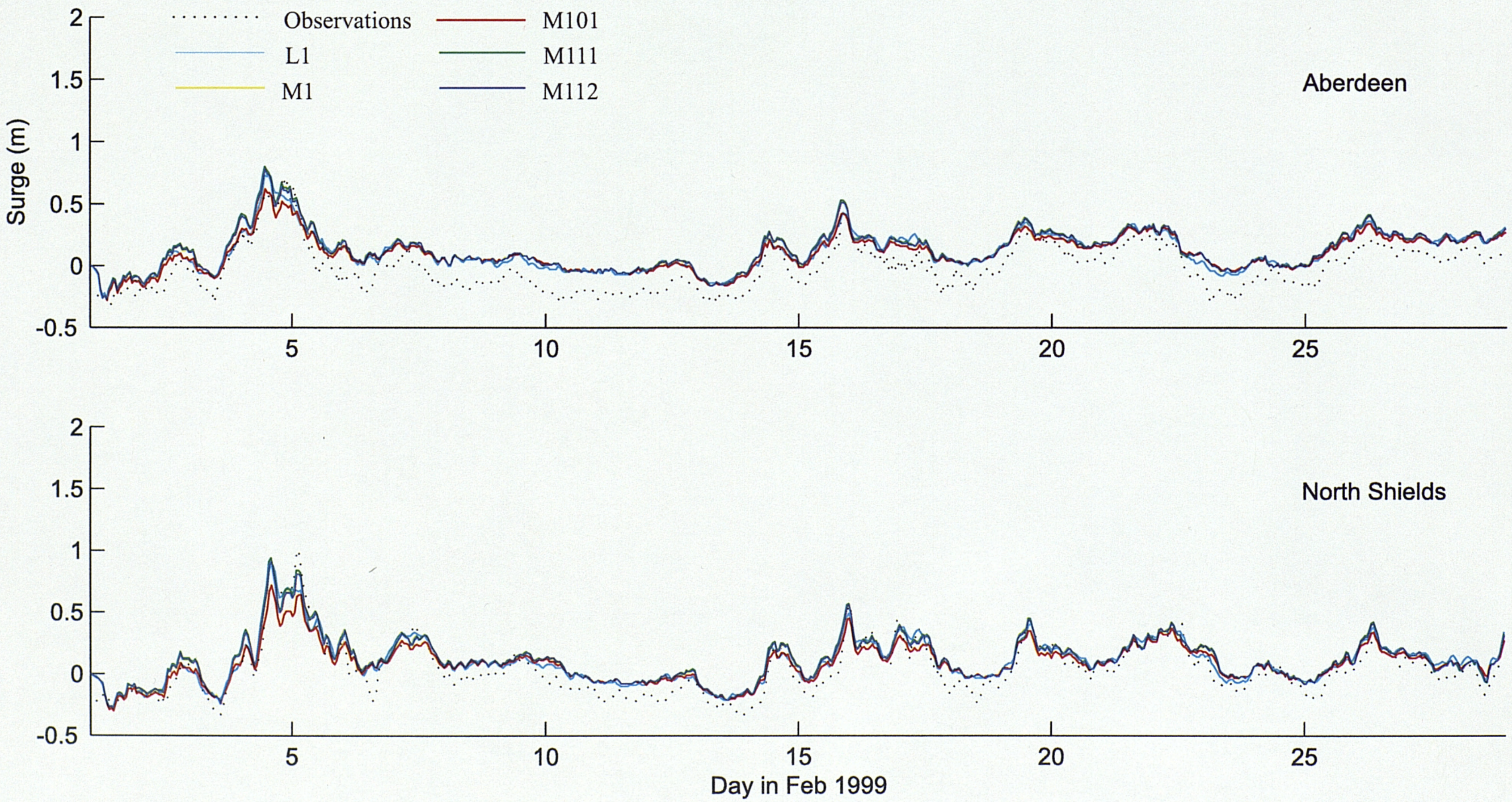

Figure 4. Comparison of model and observed surges

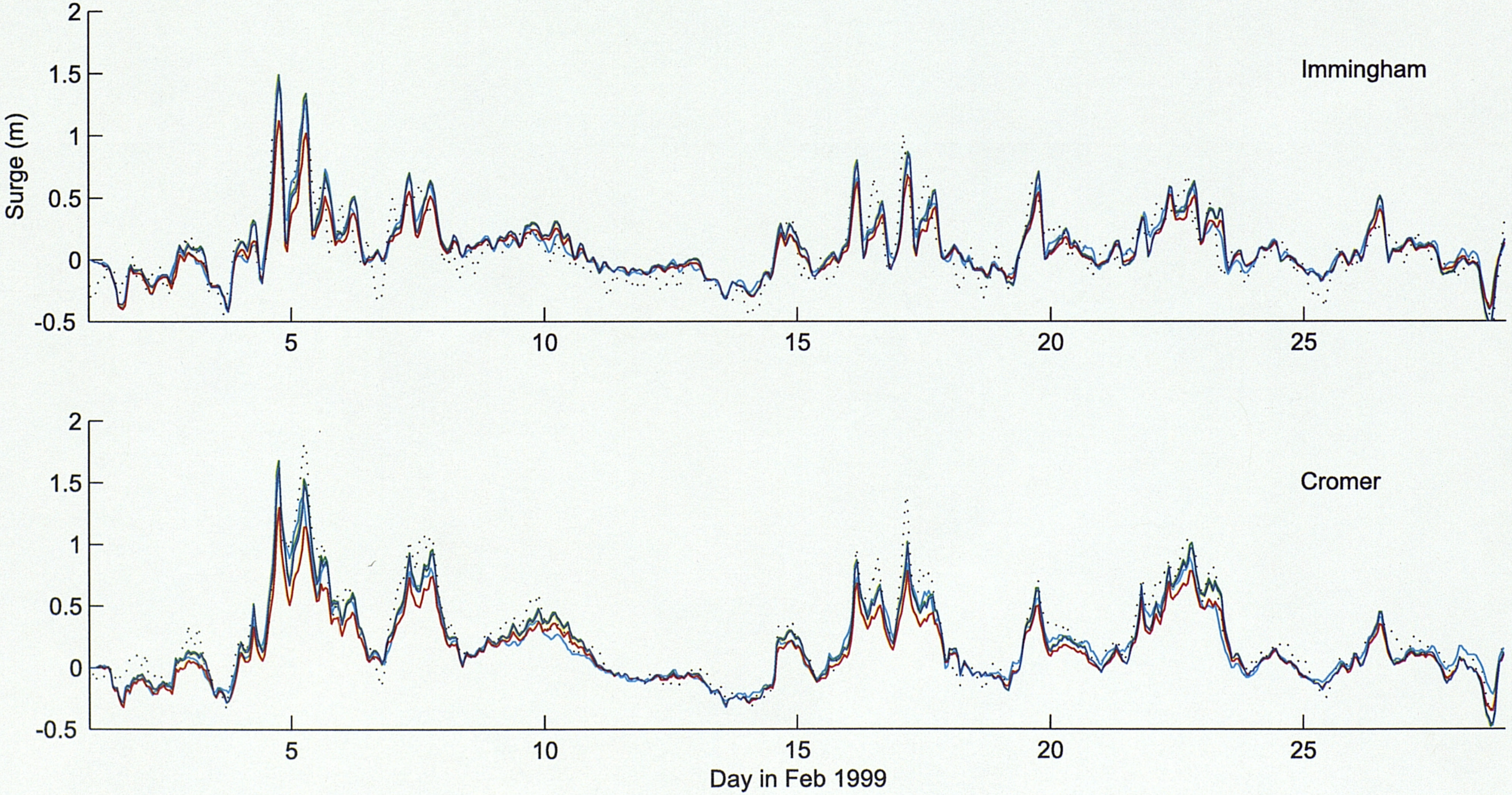

Figure 4. ../Continued

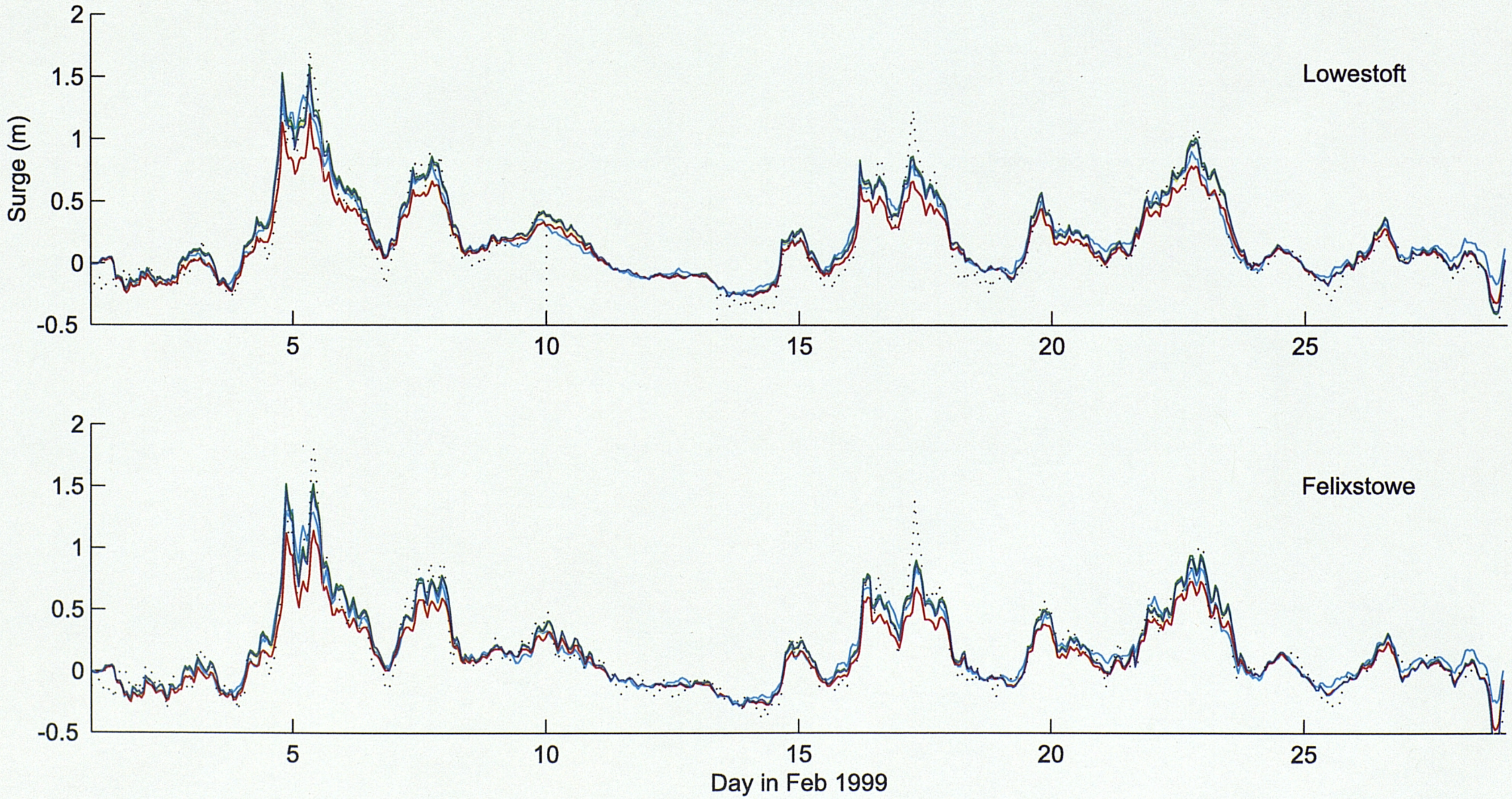

Figure 4. ../Continued

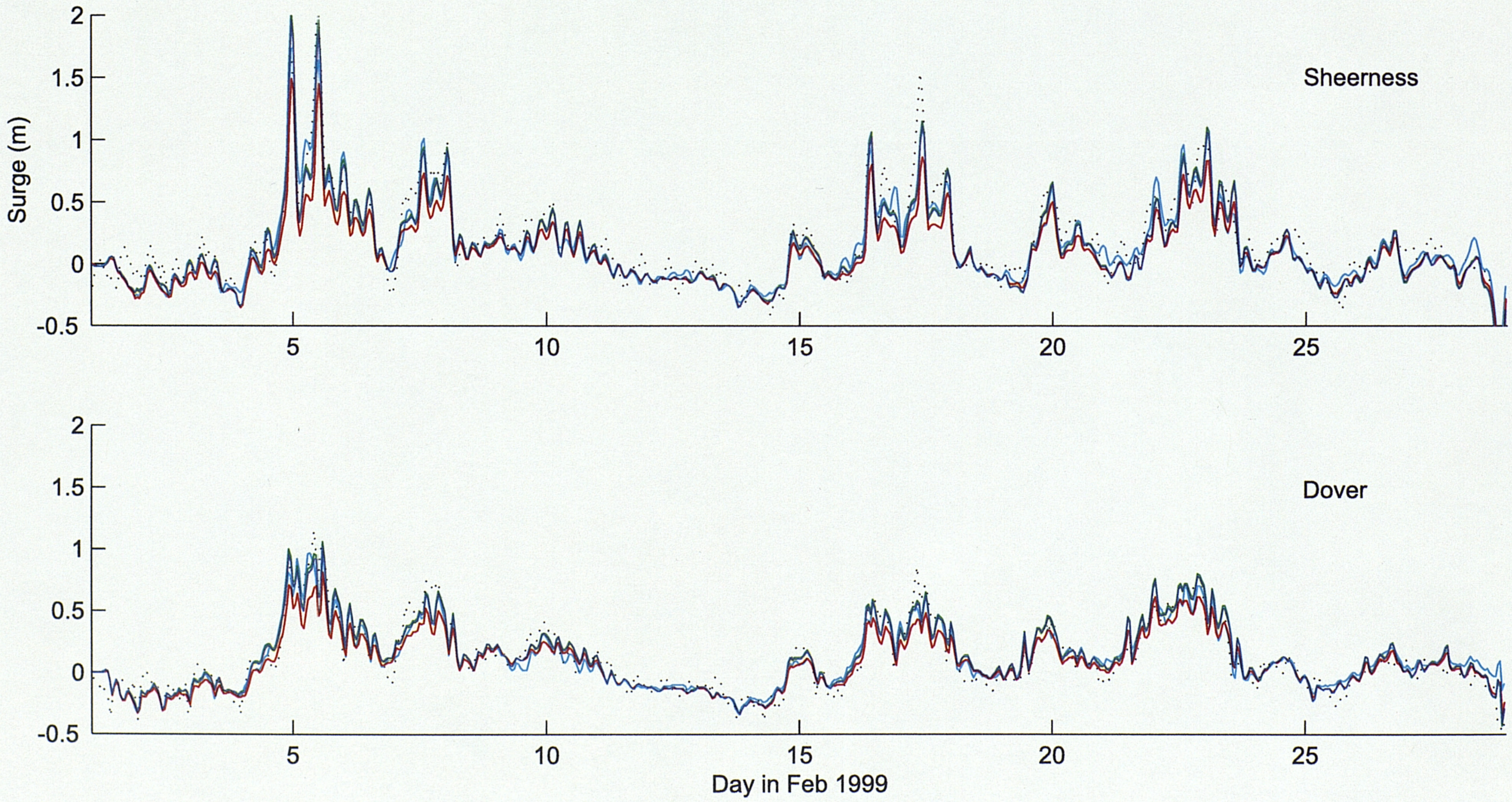

Figure 4. ../Continued